Spacecraft Radar As A Means For Studying The Antarctic

by

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POSSIBLE USES OF RADAR ON SPACECRAFT IN CONTRIBUTING TO ANTARCTIC MAPPING, CREVASSE, SEA ICE, AND MASS BUDGET STUDIES

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ABSTRACT

Studies of Antarctic ice conditions have been hindered as much by adversities of working conditions as by the need for basic terrain maps of the continent. Evidence accumulated to date suggests that multi-frequency, polypolarization radar systems mounted on orbiting spacecraft will usefully complement ground-based studies in tackling gross scale mapping problems in Antarctica. Multi-frequency radar systems can be used in an all-weather, day-or-night program for producing imagery from which reconnaissance and larger scale maps as well as statistical data can be derived. Extended over a period of time significant information may well be obtained relating to: a) mass budget of ice; b) calving rates and seasonal limits of pack ice; c) depth of pack ice and annual progress of freeze-up and break-up of Antarctic seas; d) development and persistence of fracture and crevasse patterns; e) variations in surface and subsurface conditions of ice; f) presence of melt water; g) macro-morphology of ice with reference to striations and foliations; h) local and regional topographic relief to within the capabilities of particular radar systems.

RÉSUMÉ

Les études des états de la glace en Antarctique ont été autant gênées par les adversités des conditions de travail que par le manque de cartes de base du continent. Les résultats obtenus jusqu'à maintenant indiquent que les systèmes de radar de polypolarisation à multifréquence montés dans les satellites sur orbite compléteront utilement les études faites au sol en élucidant les problèmes de la réalisation des cartes à grande échelle dans l'Antarctique. Les systèmes de radar à multifréquence peuvent être utilisés dans un programme qui peut comporter toutes conditions atmosphèrique, de jour ou de nuit, afin de produire les images desquelles peuvent dériver les cartes de reconnaissance et celles à plus grande échelle aussi bien que les données statistiques. Étendues sur un certain laps de temps, les informations significatives peuvent bien être obtenues en relation avec: a) l'amoncellement des glaces; b) les taux de vêlage et les limites saisonnières d'embâcles; c) la profondeur d'embâcle et le progrès annuel de gel et de débâcle des mers de l'Antarctique; d) le développement et la persistance des types de fractures et de crevasses; e) les variations des états de la glace en surface et en profondeur; f) la présence de l'eau provenant de la fonte; g) la macro-morphologie de la glace en référence avec les striations et foliations; h) le relief topographique local et régional au sein des capacitiés des systèmes particuliers de radar.

Introduction

Radar has many valuable capabilities as a tool in geoscience research. These capabilities have improved very rapidly since World War II, particularly in connection with side-looking imaging systems. The mating of this new technology with that of an even newer one, manned orbiting spacecraft, will open up new opportunities for scientific and practical resource-oriented studies of the earth. It is the purpose of this paper to outline the relevant characteristics of radar systems and to give some of the possible contributions of radar on spacecraft to polar ice studies.

To evaluate contributions from new radars it will be necessary to aircraft-test the equipment on ice cap and sea ice areas prior to and synchronous with the first orbital radar missions. As a preamble to these, and as a valuable temperate-glacier study in its own right, the National Aeronautics and Space Administration (NASA) is sponsoring test flights of remote sensors, including radar, over South Cascade Glacier, Washington, beginning in late 1965. Field, laboratory, and remote sensor studies are to be made under the direction of Dr. Mark Meier of the USGS.

During the last year NASA has sponsored studies at the University of Kansas, Ohio State University, the Geodesy Intelligence Mapping and Research Development Agency (U.S. Army Corps of Engineers), and a number of other institutions related to scientific uses of radar on spacecraft. As a result of the studies these institutions have recommended the use on spacecraft of synthetic-aperture radars to provide imaging in three frequencies, centered at .5, 2, and 8 gc. Images will be produced with direct and cross polarization at each frequency, and will be presented in congruent geometry to aid geoscience interpretation. Radar altimeter-scatterometers were also recommended at 0.4 gc and 8 gc.

Radar Imagery

The imagery produced by these side-looking radars is a substantially planimetric, equivalent ground-range display (Figure 2). The wavelengths used are such that the information content of radar imagery differs from that of the visible spectrum; hence it is a new dimension in our understanding of the earth's surface features. Also, the resolution is such that the clutter of redundant detail is reduced, and areas as much as 40 by 40 miles can be displayed in film five inches square. Radar imagery of this type is thus a useful generalizing tool for studies of the natural landscape.

The radar return signal is a composite related to surface roughness parameters, dielectric properties, polarization, volume scatter of penetrating waves and the angular dependence of the above (Pierson, Scheps, and Simonett, 1965). Despite the complexity of the return, radar imagery has found extensive use, particularly in geology, which at this time has seen its widest use.

The frequency spread from 8 to 0.5 gc is such that over snow and ice the short wavelength system will have a limited penetration (the dielectric in snow and ice is temperature-dependent, and skin depth is frequency-dependent) and will see many surfaces as rough. At the other extreme, .5 gc, penetration of dry snow or even ice will probably be considerable (Waite and Schmidt, 1962). Also, the return signal need not be dominated by the surface roughness. The spread of frequencies thus will give a wider range of information than a single frequency. In the same manner (as far as Antarctic ice studies are concerned) the use of multiple polarization rests on the knowledge that firn, ice and fresh snow may be variably anisotropic in their scattering properties based on anisotropy of crystal orientation, bedding, crusting, included air bubbles, foliation, and so on, and hence may be separable by working with a number of polarizations. Multifrequency, polypolarization, coherent high-resolution radar is expected to be a powerful tool in the identification of many ice features from orbit. Problems of Faraday rotation will be encountered with the longer wavelengths, but the use of multiple polarization may help overcome this expected problem.

Radar Altimetry-Scatterometry

Radar altimeters at orbital altitudes are coarse resolution instruments in area, for they average over tens of square miles, but they can be very accurate over the sea. Over the land their precision is less. They may also be used as scatterometers to measure back-scattering coefficient as a function of viewing angle (σ_0 vs. Θ). The curves so obtained vary considerably with terrain and radar frequency, and hence may serve to differentiate on a gross scale between snow and ice surfaces in broad gently sloping areas.

In polar orbit the accuracy of running radar average surface profiles will depend on the accuracy with which spacecraft position is known, on undulations of the geoid, the stability of the platform, and the methods used for extrapolating from sea level into the interior of Antarctica. The remaining unknowns relate to variations in aspect and relative relief within the patch illuminated by the radar signal. Where slopes are relatively smooth, continuous and of slight gradient, as in parts of the high plateau of Antarctica, the residual errors from sloping terrain would be tolerable. It should prove possible to profile the interior to an absolute accuracy of $\pm$ 50 meters or better, and a running accuracy of 5 meters or less. Robin (1965) has presented a clear analysis of these expected problems.

Laser Altimetry

While radar altimeters can be of fine precision over the sea, lasers hold equal promise for land surfaces. On spacecraft, they could have a resolution of ten or twenty meters, and an accuracy relative to the orbit of some tens of centimeters. The power requirements arising from the low efficiency of laser systems are at present prohibitive for space use, but this is an area of constant technological advance, and within five or six years laser altimeters suitable for spacecraft may be available. Extremely detailed profiling of the Antarctic surface, including the steep slopes of glacier chutes, should then prove feasible when clouds are absent.

Related Electromagnetic Ground and Aircraft Studies

Related data will come from the synchronous acquisition of depth of sea ice and depth to bedrock of Antarctic ice. A number of studies (Bailey, Evans, and Robin, 1964; Waite, 1964) indicate that this is possible with long wavelength radar systems, either on the ground or in low-flying aircraft. A spacecraft mount faces a number of difficulties not yet resolved. In radio echo sounding through the Brunt Ice Shelf, Antarctica, Walford (1964) has obtained results indicating further study is also necessary on sea-ice sounding.

Antarctic Mapping and Profiling

Lack of contour maps has hindered progress of scientific studies, including mass budget studies in polar regions. Obtaining such maps for Antarctica is difficult with normal survey techniques (Brandenberger, 1964). During the last decade radar mapping capability has increased remarkably, as summarized and referenced in Pierson, Scheps and Simonett (1965), and there is every indication that spacecraft-borne imaging and altimeter systems can usefully supplement normal photogrammetric methods in making topographic maps of the continent.

The location of ice depth profiles obtained from ground traverses could perhaps be obtained by placing large radar corner reflectors along the traverses, for detection on radar imagery. Comparison of bedrock topography profiling with detailed surface contours would appreciably aid studies of glacier flow, and would help demarcate drainage basin limits for studies of Antarctic drainage systems (Giovinetto, 1964).

Glacier Flow and Crevassing

Significant information on variations in regional or drainage-basin ice flow may be obtained by surface profiling, and also perhaps by following the movement of large radar corner reflectors on time-lapse radar images, as suggested by Scheps (1957) and Simonett (1964).

The development and persistence of crevassing should also be amenable to study with imaging radars. Visual crevasse detection on the surface or by aerial photography is hazardous as well as being restricted by darkness, blowing snow, or snow fill. McLerran (1965) points out that infrared scanners on low-flying aircraft are superior to conventional aerial photograhy in crevasse detection, but they vary in reliability with the time of day and with the wind, which may erase surface thermal contrasts.

Radar does not depend on thermal contrasts nor is it hampered by cloud cover, haze, or blowing snow, and it will be of finer resolution than spacecraft thermal imagery. Orbital imaging radars, thus should help reduce error in detecting and mapping the geographic distribution of crevasses and regional variations in major crevasse patterns. This could lead to a clearer understanding of their causes and of the effects ice and subsurface parameters have on crevasse occurrence (Meier, 1958).

Several structural and surficial features in addition to crevassing are of interest to glaciologists. We anticipate that imaging radar will detect anticlinal firn folds and rumples (Reid, 1964), ice rifts, glacier waves (Cameron, 1964), and perhaps sastrugi. The first two could possibly be used to infer areas of stress and direction of movement. Studies of sastrugi are of interest to ground travel and landing aircraft, and may add to our knowledge of wind system direction and strength in vast, uninstrumented areas of the Antarctic continent. While spacecraft radars would not have the resolution to map sastrugi, it is possible that surface roughness and gross lineations related to sastrugi would be detected.

Lakes and meltwater bodies, including ice caldera, have been of recent interest in glaciological studies. Koerner (1964) has suggested that ice caldera may be formed either by volcanic heat or by englacial or subglacial drainage. From the persistence of ice caldera and thermal anomalies as shown by infrared and radar imagery, we could infer areas of volcanic heat, and in addition, might add to our knowledge of subglacial or englacial drainage.

Figure 1 shows oriented Arctic lakes on unclassified AN/APQ-56 imagery (35 gc) east of Point Barrow, Alaska. Several lakes are partially dry, as indicated by the strong (light) return on the positive imagery. This interpretation was confirmed by comparison with the Harrison Bay 1:250,000 USGS topographic maps. The remainder of the lakes (dark) are ice covered, as indicated by the radar gray-scale value and the presence of pressure ridges and fracture patterns on the ice surface. The marked difference in relative dielectric and smoothness of ice and fresh water normally makes for clear distinction between the two surfaces on radar imagery.

Mass Budget Studies and Iceberg Calving

Cameron (1964) has commented that:

> Little information is available at present on the amount of ice being discharged to the sea by the Antarctic ice sheet. To obtain a realistic appraisal of the mass balance of the ice sheet this discharge along the coast and the amount of snow accumulation over the entire ice sheet must be known. Today the distribution of snow accumulation over the continent is relatively well known...(and) the positive side of the mass balance is fairly well established. However, the total loss of ice from the continent by calving, surface and bottom melting, and sublimation is little known. Calving, or ice discharge by icebergs, is by far the major form of ablation, possibly amounting to 95%. Thus, for a complete understanding of the mass balance of the Antarctic ice sheet the rate of discharge along the coastline must be determined.

Calving is hard to study from the ground. However, continued monitoring with radar in the winter and with both radar and photographs in the summer would define this parameter with hitherto unattainable accuracy for thousands of kilometers of coastline for sample periods of time. The coastline would be monitored at six-day intervals, displacing orbits 2° every 12 hours. Radar-derived estimates of ice velocity obtained by tracking corner reflectors could then be used as a further check on the calving data. Local and regional variations in both parameters could be delineated, and anomalous areas demarcated for closer scrutiny. It is of course recognized that calving may vary markedly from time to time over long spans of years and that sample data for a single season or year need not depict the long-run average. However, radar-derived estimates of ice velocity, if feasible, should give meaningful estimates related to discharge.

A considerable amount of money is spent each year in tracking icebergs as they move into shipping lanes. High-resolution imaging radar can obtain data at the critical times of the year in the North Atlantic when widespread cloud cover makes infrared scanning systems inoperable (Simonett, 1964).

Once the icebergs have calved, their movement and dissolution can

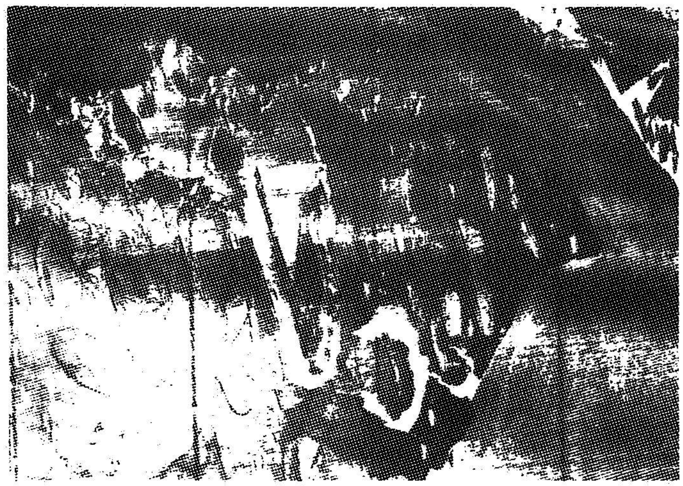

Figure 1

Oriented Arctic lakes
East of Point Barrow, Alaska

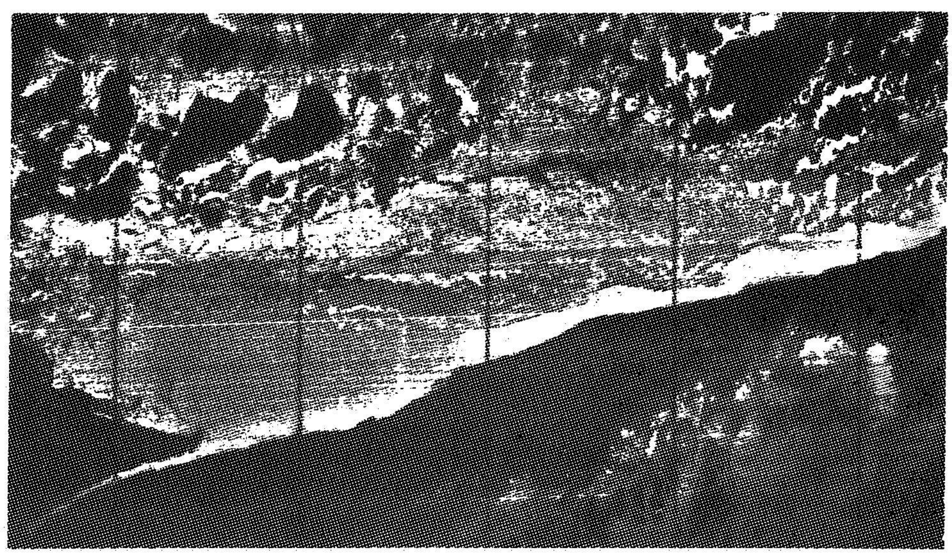

Figure 2

Radar imagery of sea ice
Colville Delta, Alaska Scale 1:350,000

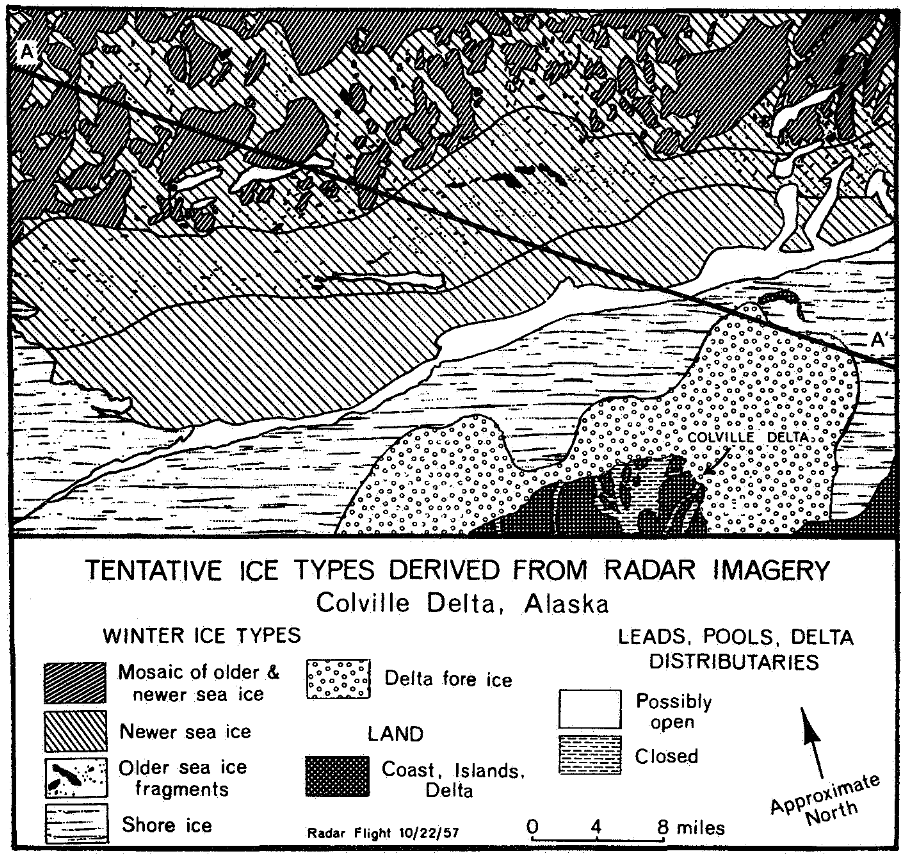

Figure 3

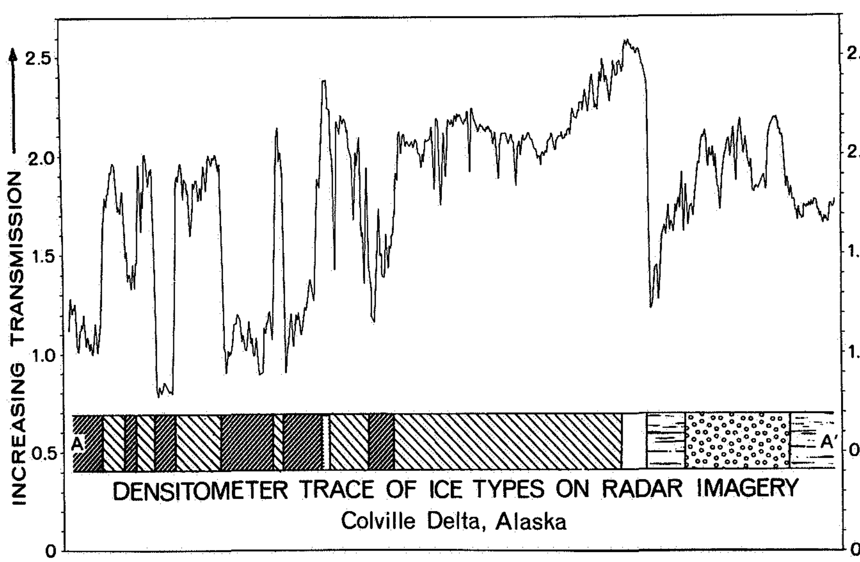

Figure 4

be plotted. Data on their routes and rates of movement would be of immense value in high latitude oceanic and atmospheric circulation studies (Simonett, 1964), for shipping forecasts, and for the routing of ships. The effect of severe storms on the paths of icebergs and the comparative attrition of grounded and moving bergs could also be studied.

Sea Ice

The magnitude of the world sea ice problem is so great because relatively little is known about ice distribution, types, origin, movement, and disappearance. Heap (1964, 1. 308) observes that:

> What little is known about the distribution of Antarctic sea ice suggests that, although simple in general outline, it is liable to much greater variations than in the Arctic, making the lack of observed material doubly hampering. As a result, it is only possible to make qualified statements about the general distribution of Antarctic sea ice, while giving more attention to the scale and causes of observed variations.

Aircraft PPI radar was used by Cameron (1964) to study ice movements in the Gulf of St. Lawrence. He considered that stereo time-lapse methods to plot the direction and speed of ice masses were feasible and should be applicable in Arctic waters.

Figure 2 is AN/APQ-56 radar imagery with a spatial resolution of 30 meters and a scale of 1:350,000 of the Colville Delta, Alaska, latitude 71°, showing several types of ice off-shore. Figure 3 is a map giving an interpretation of this image, and Figure 4 is a densitometer trace run along the line A - A' (Figures 2 and 3) to show in graphic form the differences between ice types. In making Figure 4, the antenna pattern of the imagery was calibrated and used to correct the original densitometer trace. The terminology we have used to separate ice lithologies is tentative, and deliberately does not follow international conventions because no field observations were made at the time of flight. Practically all the sea ice appears to be winter ice, with characteristic ice-finger rafting though a few remnants of true Old sea ice may be present. Our use of qualifying terms "older" and "newer" in Figure 3 is relative only and has no conventional connotation.

Ice types were separated on the basis of film density (strength of radar return) and fluctuation patterns. Large dark areas in the north and ice fragments in the center of the negative image are areas of high return, which we interpret as probably "older" winter ice. This ice is highly fractured, indicating much movement. There are some suggestions of pressure ridging and this ice may also be thicker than the "newer" ice. The lightest areas are either open water or water very thinly iced. Pale to intermediate gray tones with a delicate fracture pattern in the sea ice were considered to be very recently formed, or "newer" ice, as indicated by their enclosure of the darker ice types.

Land areas are readily separable from shore ice, and from delta fore ice. The first is probably fast ice, with some indications of pressure ridging. The outer edge is coincident with the edge of a shallow submarine shelf (see Harrison Bay 1:250,000 USGS topographic sheet). The delta fore ice gives the appearance of being fast ice under-run by fresh water. Some pools and fresh water ice may also be present. Temperature records along the land rim of the Arctic Basin were inspected for the first three weeks in October, 1957, preceding the radar flight on the 22nd. More than 80 percent of the days over this vast region had average temperatures between -2^{o} C and -15^{o} C.

Fracture and gray tone patterns lead us to infer that the "newer" sea ice closest to the shore formed after the older ice had drifted some three to five kilometers away from the fast ice.

This radar imagery was obtained through a continuous stratiform overcast from midnight to midnight over the arctic slope on October 22, 1957. This demonstration of the virtually all-weather capability of even a short wavelength system emphasizes the utility of radar in cloudy areas over sea ice where photography and infrared scanning would be severely handicapped.

These tentative interpretations are based on single polarization, single frequency, short wavelength radar. We believe that a spread of frequencies and polarizations will permit firmer identifications of ice type, roughness, and ice thickness. Continued monitoring would also allow maps of ice drift and seasonal change to be produced. In Antarctic waters a study of winter sea ice movements would fill a gap equivalent to that on regional winter velocities of glacier ice.

Acknowledgements

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References

Bailey, J.T., S. Evans and G. de Q. Robin. "Radio Echo Sounding of Polar Ice Sheets," Nature, Vol. 204, 1964, pp. 420-421.

Brandenberger, A.J. "Aerial Triangulation in the Antarctic," Photogrammetric Engineering, Vol. XXX, 1964, pp. 197-201.

Cameron, H.L. "Ice-Cover Surveys in the Gulf of St.Lawrence by Radar," Photogrammetric Engineering, Vol. XXX, 1964, pp. 833-841.

Cameron, R.L. "Glaciological Studies at Wilkes Station, Budd Coast, Antarctica," Antarctic Research Series, Vol. 2, NAS-NRC, Publication #1197, 1964, pp. 1-36.

Giovinetto, M.B. "The Drainage Systems of Antarctica: Accumulation," Vol. 2 Antarctic Research Series, NAS-NRC, Publication #1197, 1964, pp. 127-156.

Heap, J.A. "Pack Ice," Antarctic Research, edited by Sir Raymond Priestly, Raymond J. Adie and G. de Q. Robin. Butterworth (London: 1964) pp. 308-317.

Koerner, R.M. "An Ice Caldera Near Hope Bay, Trinity Peninsula, Graham Land," British Antarctica Survey Bulletin, No. 3, May 1964, pp. 37-39.

McLerran, James H. "Airborne Crevasse Detection," Proceedings of the Third Symposium on Remote Sensing of the Environment (Infrared Laboratory, IST, University of Michigan), October 14-16, 1964 (February 1965) p. 801.

Meier, M.F. "The Mechanics of Crevasse Formation," Union. Geodesique et Geophysique Internationale. Association Internationale d'Hydrologie Scientifique Assemblee generale de Toronto, 3-4 September, 1957 (published 1958) Tom. 4, pp. 500-508.

Pierson, W.J., B.B Scheps and D.S. Simonett. "Some Applications of Radar Return Data to the Study of Terrestrial and Oceanic Phenomena," Third Goddard Memorial Symposium of the American Astronautical Society, Washington, D.C. March 18-19, 1965. pp. 1-40.

Reid, J.R. "Structural Glaciology of an Ice Layer in a Firn Fold, Antarctica," Antarctic Research Series, Vol. 2, NAS-NRC, Publication #1197, 1964, pp. 237-266.

Robin, G. de Q. Paper to be presented at the Symposium on Glacier Mapping, Ottawa, September 22, 1965.

Scheps, B.B. "Terrains," (Terrain Radar Interpretation Study) U.S. Geological Survey, 1957.

Simonett, D.S. "Possible Uses of Radar for Geoscience Purposes from Orbiting Spacecraft," Manuscript presented to Planetology Subcommittee National Aeronautics and Space Administration, Chicago, October 27, 1964, pp. 1-11, Center for Research in Engineering Science, CRQ 61-2, The University of Kansas, Lawrence, Kansas.

Waite, A.H. "Ice-Depth Sounding with Electromagnetic Waves, Arctic and Antarctic," a paper read to the National Academy of Science, Committee on Polar Research, 1964, pp. 1-30.

Walford, M.E. "Radio Echo Sounding Through an Ice Shelf," Nature, Vol. 204, 1964, pp. 317-319.

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